

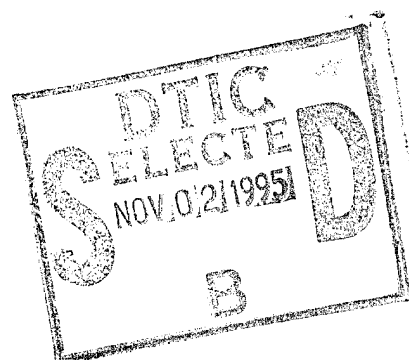
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Technical Report ARAED-TR-95014

**PICATINNY ARSENAL CYLINDER EXPANSION TEST AND
A MATHEMATICAL EXAMINATION OF THE EXPANDING CYLINDER**

Brian Edward Fuchs



October 1995



US ARMY
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INTRODUCTION

Warhead designs use explosives to accelerate components to high velocities. To measure the effectiveness of an explosive, the cylinder expansion test is used. The test measures the wall acceleration of a copper cylinder after the explosive inside has detonated. The Gurney constant is calculated from the results and is used to predict the velocity in other geometry's. The results of the test are also used in the determination of equations of state required in computer modeling of warhead systems.

In the research and development of new explosive molecules and formulations, quantities of materials are frequently limited. Small laboratory batch processes would have to be repeated a number of times in order to produce the quantity required for full scale performance testing, making the test extremely expensive. In order to decrease the cost and make performance testing, a down selection criteria available earlier in the development process, a reduced scale cylinder expansion test has been developed.

The new test uses smaller cylinders, 3/4 in. inner diameter (I.D.), 1 in. outer diameter (O.D.), and 10 in. long, than the conventional larger test, which is 1 in. I.D., 1.2 in. O.D., and 12 in. long. The volume within the cylinder and the amount of explosive required is reduced by 53%. To directly compare the results to the larger test a new Gurney equation was developed. The analysis for the first time introduces variable velocities due to the thinning of the wall during expansion. This allows cylinder tests of different geometry's to be compared to each other.

BACKGROUND

Gurney's Method

R. W. Gurney developed a method for determining the velocity of fragments accelerated by a detonation. The Gurney method is simplistic, but the results obtained correlate well with experiments. The model assumes a linear velocity distribution throughout the reacted gases, and a constant velocity in the wall. This assumption creates a partitioning of the available kinetic energy between the gases and the wall. For an explosive driving a cylinder

$$V = \sqrt{2E} \left[\frac{1}{\left(\frac{M}{C} + 1/2 \right)} \right]^{\frac{1}{2}} \quad (1)$$

(refs. 1 and 2)

where

$$\begin{aligned} V &= \text{fragment velocity} \\ \sqrt{2E} &= \text{Gurney constant (units of velocity)} \\ \frac{M}{C} &= \text{wall mass to explosive charge ratio} \end{aligned}$$

A useful engineering approximation assumes the Gurney value to be a constant for the material. For this reason, it is referred to as the Gurney constant. The actual value varies and is related to many other variables, such as the level of expansion, break-up of the wall releasing detonation products, the axial flow of the reaction products, and the shock waves from the detonation.

The equation assumes that the detonation wave impacts the wall simultaneously along its surface. For a cylindrical geometry the detonation wave normally travels along the axis of the charge. The detonation adds an axial velocity component. The relationship between the velocity and its normal component is given by

$$V = 2D \sin(\theta/2) \quad (\text{ref 1}) \quad (2)$$

where

$$\begin{aligned} D &= \text{Detonation velocity} \\ \theta &= \text{Angle of the tube wall to the initial position} \end{aligned}$$

For many engineering problems all that is required to obtain a good estimate of fragment velocities, is to obtain a reasonable value for the Gurney constant from testing or other methods. Equation 2 is for a cylindrical geometry, but with similar assumptions the equations for many other geometries can be obtained. The Gurney constant calculated from one geometry can be applied, with varying levels of success, to other geometries.

PICATINNY ARSENAL CYLINDER TEST

Experimental Setup

In measuring the Gurney constant, the cylindrical geometry is most often used. It is relatively accurate, easy to manufacture, and easy to obtain measurements from. In the conventional test, as described in reference 3, the cylinder is made from soft oxygen free copper. The walls do not instantaneously obtain the maximum velocity as assumed in the Gurney analysis. These tubes allow for large expansions of the plastically deformable copper before rupturing. In the conventional test, the tubes are 1 in. I.D., 1.2 in. O.D., and 12 in. long. Other, usually larger, cylinders have been used.

The Picatinny Arsenal cylinder expansion test uses a slightly different geometry (fig. 1). The slightly smaller tubes are 0.75 in. I.D., approximately 1 in. O.D., and 10 in. long. The smaller geometry uses a little less than half of the explosive required for the larger test. This is a significant savings for research materials that are made in very small quantities. The walls are thicker than the conventional test. This allows for further expansions before breakup and changes the charge to mass ratio (C/M) of the test. A typical Picatinny Arsenal test will have a C/M of about 0.25, which would be 0.442 for the conventional cylinder expansion test for an explosive of the same density.

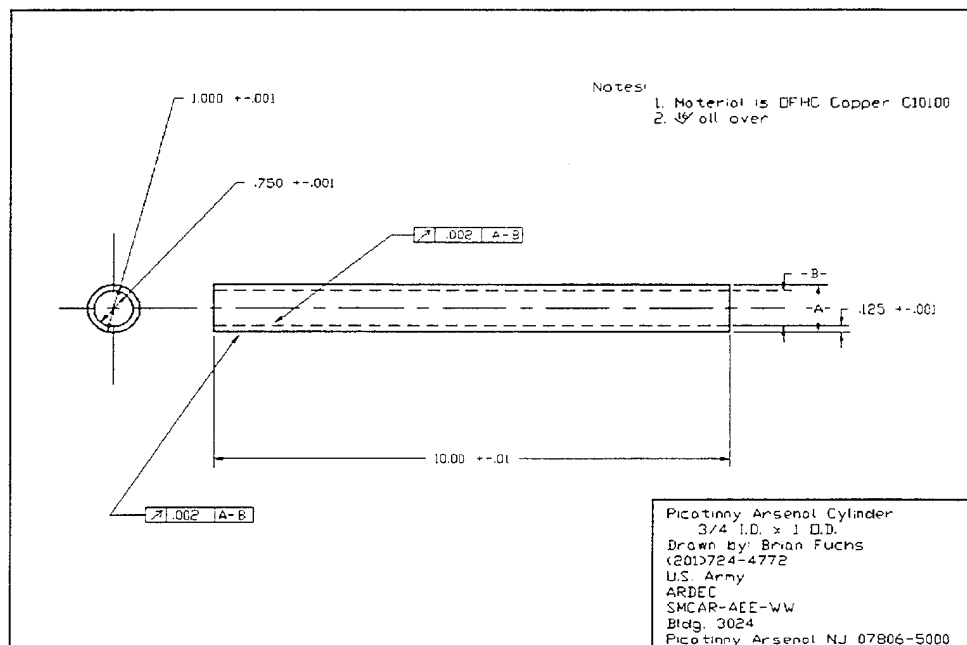


Figure 1
Picatinny Arsenal cylinder

The wall and detonation velocities are obtained in the same manner as for the conventional tube. A streak camera is used to record the expansion of the cylinder walls. The camera is typically run at a writing rate of 1 mm/ μ s, allowing the film image to fit on the screen of the motion analyzer. The image of the copper cylinder is located in the center of the field of view, allowing for the analysis to be conducted on both sides of the tube. The slit of the camera is located approximately 6.5 in. from the top of the tube. This places the slit far enough from the ends to avoid rarefactions from effecting the results. If the explosive fill consists of individual pellets, the slit is moved until it is located away from the edges of any of the pellets. This avoids any detonation

transfer problems and any air in this region from adversely effecting the results. To assure the detonation is well established before entering the cylinder, 2 to 3 in. of run up are used. This long run up replaces the expensive plain wave generator that is sometimes used.

The tube is back lighted with an argon bomb (fig. 2). For this, an argon filled toy balloon is used (ref 4) with an explosive charge taped to the back. The balloon provides about 50 μ s of usable light and is cheap and easy to use. This also reduces the cost as compared to the more expensive argon bombs typically used.

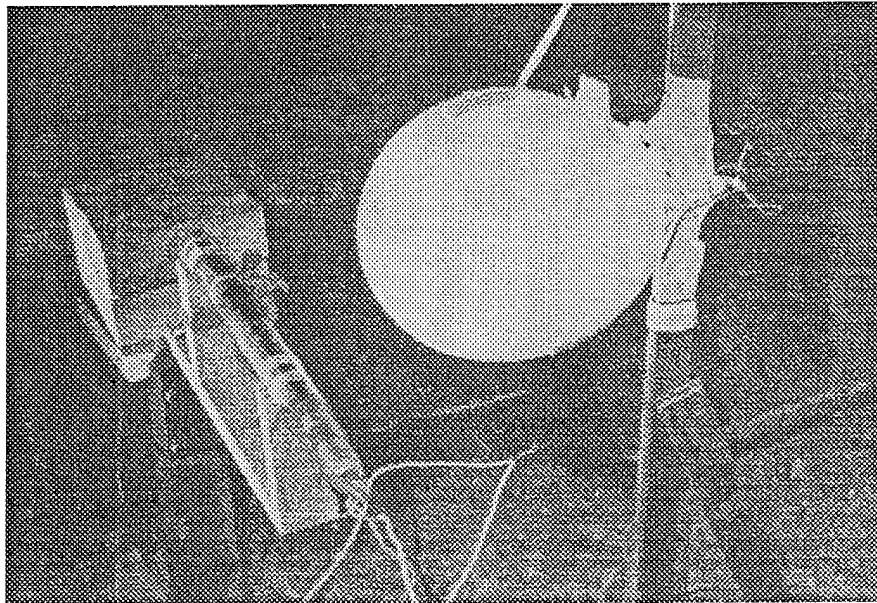


Figure 2
Experimental setup

The detonation velocity is obtained using closure pins, placed at 1 and 2 in. from either end of the tube (fig. 3 and discussions with I. Akst). In this system, the copper tube is grounded. Ordinance tape is wrapped once around the tube and copper wire of 0.004 in. diameter with cleaned ends is placed on the tape extending 3/16 in. over the side. The wire is then taped in place. This puts the copper wire laying 3/16 in. from, but not touching, the copper tube. The pins are then charged. Contact between the pins and the copper tube during the test is measured with a capacitive discharge system. An oscilloscope, recording at 5 ns per point, measures the shorting of the pins.

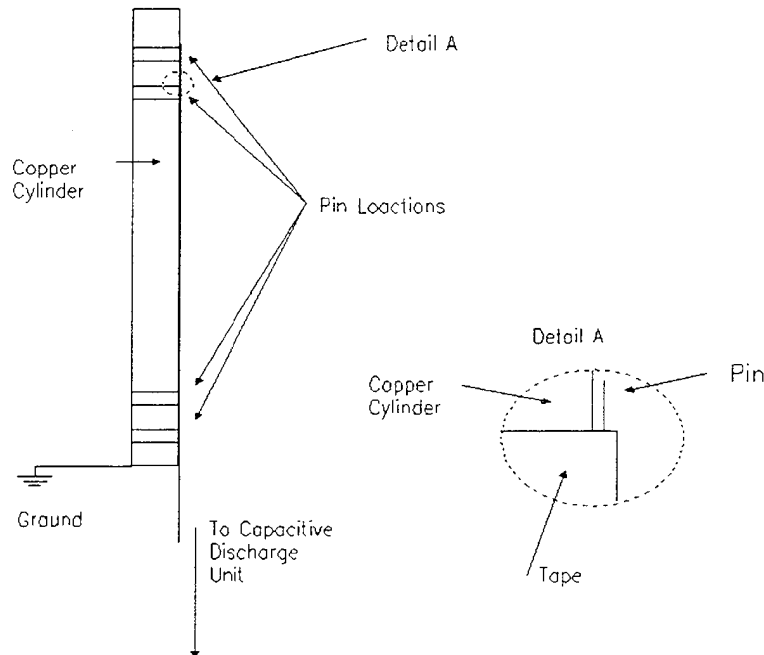


Figure 3
Closure pin locations

Analysis

The streak photograph records the position of the wall with time (fig. 4). By scaling the photograph, the position time history in full scale is obtained. A Vanguard brand motion analyzer is used to obtain the data, which is transferred into an IBM compatible personnel computer. Two programs are used, the first scales and saves the data in a file and the second calculates the Gurney values. This allows for any future modifications in the analysis without re-entering the data, a time consuming process. Generally, about 100 to 200 readings are obtained on the cylinders expansion.

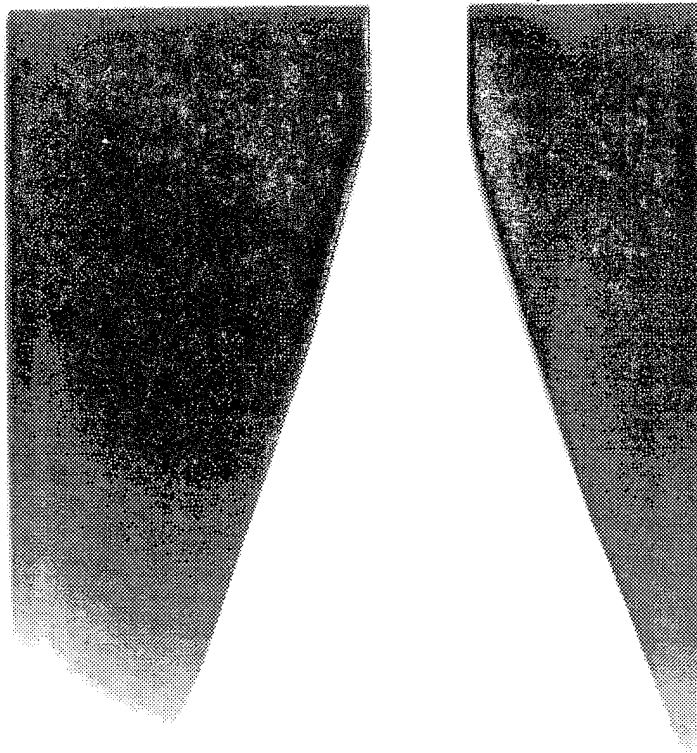


Figure 4
Typical test results

The second program analyzes the scaled data. This program performs a least-mean-square that fits the data to a fourth order polynomial. From the differential of the fitted equation, the velocity can be obtained at any point in time up to break-up.

The velocity varies in the cylinders during the expansion. The wall thins, giving the inner wall a slightly higher velocity than the outer wall. The Picatinny Arsenal cylinder test, with its heavier wall, has a larger variation of velocities than the conventional tube. A modified Gurney equation was developed that accounts for these variations, and is discussed later (Gurney Relationship for Thick Cylinders).

The program determines the velocity, and therefore the Gurney constant, at two and seven volume expansions of the inside diameter. These are the same expansions as used in conventional expansion tests. The Picatinny Arsenal cylinder has not broken up as yet at much larger expansions, obtaining at least 11.7 volume expansions of the inside diameter; but the Gurney values obtained are only slightly higher than those obtained at the seven area expansions. The seven volume expansions of the outside diameter are typically used since this is the volume expansion reliably obtained before the conventional test breaks up. The break up is readily evident as the gases jetting from the cracks make the cylinder appear to be rapidly accelerating after a long period of steady velocity. The typical output from the program is in the appendix.

VELOCITY RELATIONSHIPS OF CYLINDER EXPANSION TESTS

Purpose for Relationships

For the cylinder expansion tests, the velocity measurements are obtained on the outside diameter of the tube. Because of the thinning of the tube during expansion, the inside wall has a higher velocity than the outside. Also, the inside area expands at a rate much higher than the area measured on the outside wall. For this reason, some examination of the area, velocity, and other relationships during the expansion are useful.

Momentum Average Velocity

For a cylinder, the mass M remains constant during the expansion

$$M = \rho r_o^2 \pi - \rho r_i^2 \pi = \rho \pi (r_o^2 - r_i^2) \quad (3)$$

Change in mass with time is zero

$$\frac{dM}{dt} = 0 = \rho \pi 2 \left[r_o \frac{dr_o}{dt} - r_i \frac{dr_i}{dt} \right] \quad (4)$$

$$0 = r_o \frac{dr_o}{dt} - r_i \frac{dr_i}{dt} \quad (5)$$

Then

$$\frac{V_o}{V_i} = \frac{r_i}{r_o} \text{ and for any radius within the cylinder } \frac{V}{V_o} = \frac{r}{r_o} \quad (6)$$

The average velocity of the copper wall must be calculated based upon the mass or the energy of the wall. The first computation here uses the momentum average velocity as compared to the velocity measured on the outside wall.

For the momentum I

$$I = \int_{r_i}^{r_o} V \rho 2\pi r dr \quad (7)$$

Using the equation 7 relating the velocities and radii

$$\begin{aligned}
 I &= \int_{r_i}^{r_o} \rho V_o \left(\frac{r_o}{r} \right) 2\pi r dr \\
 &= V_o r_o (r_o - r_i) \rho 2\pi
 \end{aligned} \tag{8}$$

The momentum average velocity is then

$$\begin{aligned}
 V_m &= \frac{V_o r_o (r_o - r_i) 2\pi \rho}{(r_o^2 - r_i^2) 2\pi \rho} \quad \left[\frac{\text{Momentum}}{\text{Weight}} \right] \\
 &= \frac{V_o (r_o^2 - r_i r_o)}{(r_o^2 - r_i^2)}
 \end{aligned} \tag{9}$$

From the constraint of constant mass

$$\begin{aligned}
 r_o^2 - r_i^2 &= \text{constant for the system} \\
 &= (r_o^2 - r_i^2) \Big|_{\text{INITIAL}}
 \end{aligned} \tag{10}$$

Then

$$r_i = \left(r_o^2 - (r_o^2 - r_i^2) \Big|_{\text{INITIAL}} \right)^{\frac{1}{2}} \tag{11}$$

Then V_m becomes

$$V_m = \frac{V_o \left(r_o^2 - r_o (r_o^2 - (r_o^2 - r_i^2) \Big|_{\text{INITIAL}})^{\frac{1}{2}} \right)}{(r_o^2 - r_i^2) \Big|_{\text{INITIAL}}} \tag{12}$$

The ratio of the momentum average velocity to the outside wall velocity is shown in the following graph. The initial conditions are for the Picatinny Arsenal cylinder test. As the cylinder expands and the walls become thinner, the momentum average velocity and the outside wall velocity match closely.

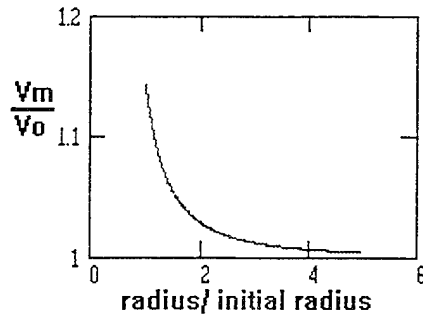


Figure 5
Ratio of momentum average velocity to outside wall velocity

This yields the momentum average velocity from the velocity of the outside wall and the outside radius. Note that for expansions in the areas of interest, the momentum average velocity and the outside wall velocity are essentially the same.

Kinetic Energy Average Velocity

Looking at kinetic energy

$$KE = 1/2 m V^2 = \int_{r_i}^{r_o} V^2 \rho \pi r dr$$

$$\text{for } V = \frac{V_o r_o}{r} \quad (13)$$

$$= \int_{r_i}^{r_o} \frac{V_o^2 r_o^2}{r^2} \rho \pi r dr$$

Solving and using a equation 10

$$KE = 2\pi \rho V_o^2 r_o^2 \ln \left(\frac{r_o}{\left((r_o^2 - ((r_o^2 - r_i^2)|_{\text{INITIAL}}))^{\frac{1}{2}} \right)} \right) \quad (14)$$

Which yields the average kinetic energy from the velocity measured on the outside of the radius and the outside diameter.

The kinetic energy average velocity

$$V_k = \left[\frac{2 \text{ KE}}{\text{Mass}} \right]^{\frac{1}{2}}$$

$$= \left[\frac{2 V_o^2 r_o^2 \ln \left(\frac{r_o}{\left((r_o^2 - ((r_o^2 - r_i^2)|_{\text{INITIAL}}))^{\frac{1}{2}} \right)} \right)}{\left((r_o^2 - r_i^2)|_{\text{INITIAL}} \right)} \right]^{\frac{1}{2}} \quad (15)$$

The kinetic average velocity divided by the outside wall velocity is then

$$\frac{V_k}{V_o} = \left[\frac{2 r_o^2 \ln \left(\frac{r_o}{\left((r_o^2 - ((r_o^2 - r_i^2)|_{\text{INITIAL}}))^{\frac{1}{2}} \right)} \right)}{\left((r_o^2 - r_i^2)|_{\text{INITIAL}} \right)} \right]^{\frac{1}{2}} \quad (16)$$

The following diagram shows the relationship between the kinetic average velocity and the measured outside wall velocity. The same trends are shown as for the momentum average velocity, the ratio nears one as the walls thin due to expansion.

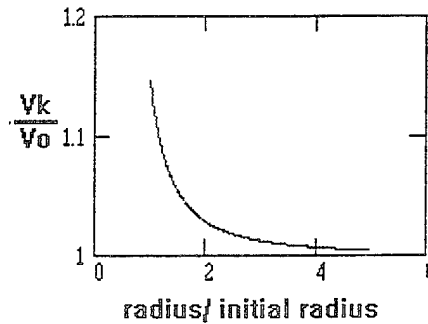


Figure 6

Ratio of kinetic energy average velocity to outside wall velocity

Measurement Errors

A rigorous analysis of the errors measurements have not been conducted. The analysis here determines the general relationships between the variables.

For the equation relating velocity and charge to mass ratio, C/M

$$V = \sqrt{2E} \left[\frac{1}{\left(\frac{M}{C} + 1/2 \right)} \right]^{\frac{1}{2}}$$

It can be seen that for smaller M/C ratios, the errors in determining the errors are not as significant if the M/C ratio is small. The errors in measuring the velocity have a much greater effect, linearly changing the calculated value of the Gurney constant.

Error From Not Accounting for the Angle of Expansion

From the relationship between angle, wall, and detonation velocities

$$V = 2D \sin(\theta/2)$$

Where V is obtained from the Gurneys relationship

The measurement used in the test is the radial position, so only radial velocities are obtained.

$$V_{\text{measured}} = V \cos\left(\frac{\theta}{2}\right) = 2D \sin\left(\frac{\theta}{2}\right) \cos\left(\frac{\theta}{2}\right) \quad (17)$$

Using trigonometric identities

$$V_{\text{measured}} = D \sin(\theta) \quad (18)$$

Then

$$\theta = \sin^{-1}\left(\frac{V_{\text{measured}}}{D}\right) \quad (19)$$

and

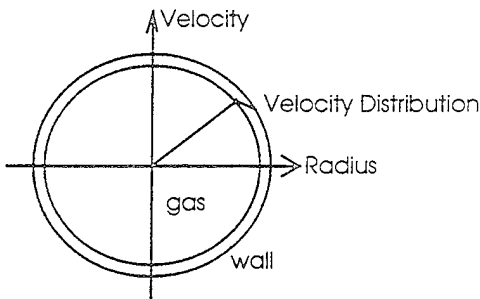
$$V = \frac{V_{\text{measured}}}{\cos\left(\sin^{-1}\left(\frac{V_{\text{measured}}}{D}\right)\right)} \quad (20)$$

For most problems, this accounts for a small percent of error between the actual and the measured velocities. This correction factor can then be ignored.

Gurney Relationship for Thick Cylinders

Previous work on the Gurney constant assumes that the wall thickness of the cylinder remains constant. This is not correct as the wall must become thinner as the tube expands. To correct for the slightly larger inside wall velocity, some researchers have applied a momentum correction to the values obtained. It is possible to obtain an expression that does not require such a fix, by applying the conservation of mass.

Velocity Distribution of Gasses and Wall



By the conservation of mass

$$V_{\text{gas}} = \frac{V_i r_i}{r}$$

V_{gas} = Gas velocity at radius r

$$V_{\text{wall}} = \frac{V_o r_o}{r}$$

V_{wall} = Wall velocity at radius r

V_o = Outside wall velocity

V_i = Inside wall velocity

r_o = Outside wall radius

r_i = Inside wall radius

By the conservation of energy

$$CE = 1/2 m V_{\text{wall}}^2 + 1/2 m V_{\text{gas}}^2 \quad (21)$$

$$= 1/2 \rho_m \int_{r_i}^{r_o} \left(V_o^2 \frac{r_o^2}{r^2} \right) 2\pi r dr + 1/2 \rho_e \int_o^{r_i} \left(V_i^2 \frac{r^2}{r_i^2} \right) 2\pi r dr$$

$$= V_o^2 r_o^2 \rho_m \pi \ln(r) \Big|_{r_i}^{r_o} + \frac{V_i^2}{r_i^2} \pi \rho_e \left(\frac{r_i^4}{4} \right) \quad \text{with } V_i = \frac{V_o r_o}{r_i}$$

$$= V_o^2 r_o^2 \rho_m \pi \ln\left(\frac{r_o}{r_i}\right) + 1/4 V_o^2 r_o^2 \rho_e \pi$$

$$= V_o^2 r_o^2 \pi \left(\rho_m \ln\left(\frac{r_o}{r_i}\right) + \rho_e / 4 \right) \quad \text{Weight of explosive, } C = \rho_e r_i^2 \pi$$

$$CE = V_o^2 \left(\frac{r_o}{r_i} \right)^2 C \left(\left(\frac{\rho_m}{\rho_e} \right) \ln\left(\frac{r_o}{r_i}\right) + 1/4 \right)$$

$$V_o^2 = \frac{E \left(\frac{r_i^2}{r_o^2} \right)}{\left(\frac{\rho_m}{\rho_e} \right) \ln\left(\frac{r_o}{r_i}\right) + 1/4}$$

$$= \frac{2E \left(\frac{r_i^2}{r_o^2} \right)}{2 \left(\frac{\rho_m}{\rho_e} \right) \ln\left(\frac{r_o}{r_i}\right) + 1/2}$$

$$V = \sqrt{2E} \left[\frac{\left(\frac{r_i}{r_o} \right)^2}{2 \left(\frac{M}{C} \right) \left(\frac{r_i}{r_o^2 - r_i^2} \right) \ln\left(\frac{r_o}{r_i}\right) + 1/2} \right]^{\frac{1}{2}}$$

Weight of the wall, $M = \rho_m \pi (r_o^2 - r_i^2)$

Weight of the explosive, $C = \rho_e \pi r_i^2$

The M/C ratio can be obtained from the equation to have it resemble the typical form in equation 1, and be based upon the outside radius position, the measured quantity in testing.

From the conservation of mass

$$r_i = (r_o^2 - (r_o^2 - r_i^2)|_{\text{INITIAL}})^{\frac{1}{2}}$$

Then

$$V = \sqrt{2E} \left[\frac{\left(\frac{(r_o^2 - (r_o^2 - r_i^2)|_{\text{INITIAL}})^{\frac{1}{2}}}{r_o} \right)}{2 \frac{M}{C} \left(\frac{(r_o^2 - (r_o^2 - r_i^2)|_{\text{INITIAL}})}{(r_o^2 - r_i^2)|_{\text{INITIAL}}} \right) \ln \left(\frac{r_o}{(r_o^2 - (r_o^2 - r_i^2)|_{\text{INITIAL}})^{\frac{1}{2}}} \right) + 1/2} \right]^{\frac{1}{2}} \quad (22)$$

This equation can be used to determine the Gurney constant for cylinders with thick walls. It also can be used to compare the test results with different cylindrical geometry's. The equation was manipulated to be dependent upon the outside radius and the initial conditions of the tube. This allows for easy analysis with the measured variables. A comparison for the Picatinny Arsenal cylinder test is given in figure 7. The effects of this equation appear more in the early expansion of the tube.

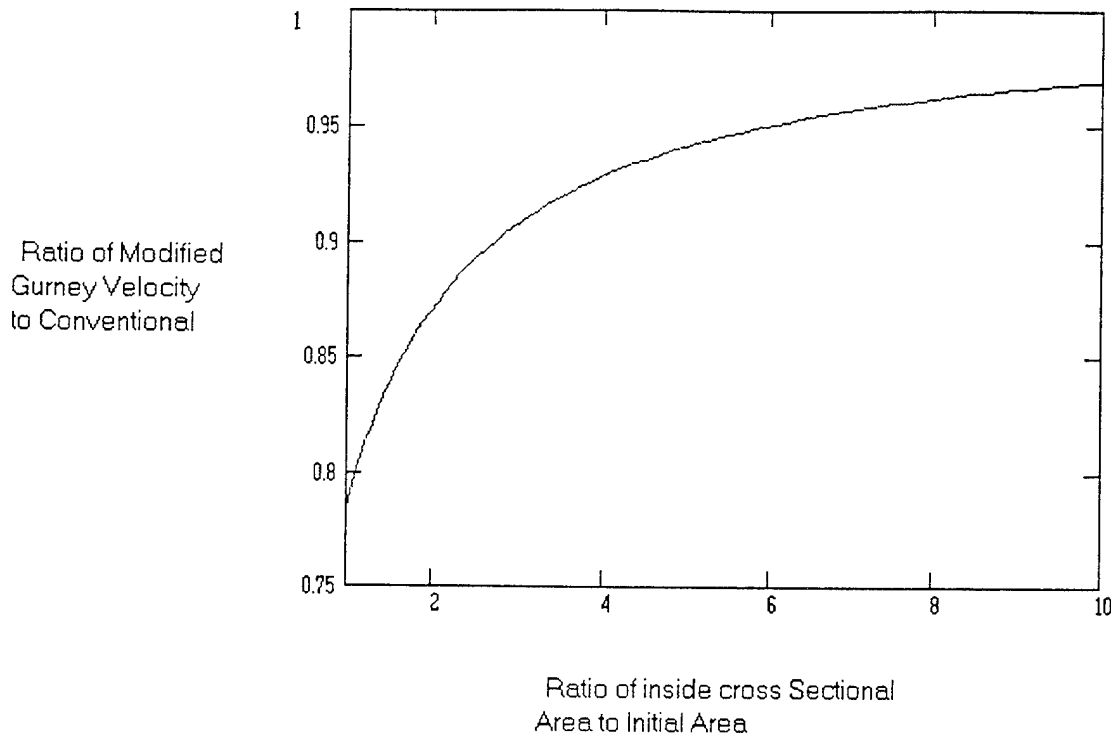


Figure 7
Ratio of modified gurney to gurney constant

SUMMARY

A smaller, relatively heavier walled copper cylinder has been incorporated into the cylinder expansion test. Modifications to the Gurney Equation that account for the stretching and thinning of the copper cylinder have been developed. The new equation allows the use of the smaller cylinders, 3/4 in. inner diameter (I.D.), 1 in. outer diameter (O.D.), and 10 in. long to the conventional larger test, 1 in. I.D., 1.2 in. O.D., and 12 in. long. This reduces the quantity of explosives required for performance testing by more than half.

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APPENDIX
INPUT AND ANALYSIS PROGRAMS

Appendix

Input Program

This program retrieves the raw data from the serial port, collects scales and other test data, and saves the data in scaled format.

```
#include <stdio.h>
#include <math.h>
double x[300],y[300];
char header[8],infile[12],outfile[12];
main()      {
    FILE *data_in;
    FILE *data_out;
    int rawcount,i;
    char xstring[7],ystring[7],tmp[7];
    double filmspeed,od,id,moverc,timescale,radiuscale,rho,DetVel;
    rawcount=0;
    printf("Key in the input file name ");
    scanf("%s",infile);
    printf("\nKey in the output filename ");
    scanf("%s",outfile);
    data_in=fopen(infile,"r");
    for(i=0;i<299;i++)
        {if(feof(data_in)!= 0) break;
        fscanf(data_in,"%s%s%s",header,xstring,ystring);
        x[i]=atof(xstring); y[i]=atof(ystring);
        }      fclose(data_in);
    rawcount=i-1;
    printf("Number of Data Points Read %d\n",rawcount);
    printf("\n\n\nBldg. #1612 Run Number 3-%s",&(header[5]));
    printf("\n\n\nEnter The Following Variables\n\n");
    printf("The M/C Ratio ");scanf("%s",tmp);
    moverc=atof(tmp);
    printf("\nThe O.D. of the Tube(inches) ");scanf("%s",tmp);
    od=atof(tmp);
    printf("\nThe I.D. of the Tube(inches) ");scanf("%s",tmp);
    id=atof(tmp);
    printf("\nThe Film Mirror Speed(R.P.S.) ");scanf("%s",tmp);
```

```

filmspeed=atof(tmp);
printf("\nThe Explosive Density (gm/cc) ");scanf("%s",tmp);
rho=atof(tmp);
printf("\nThe Detonation Velocity (mm/us) ");scanf("%s",tmp);
DetVel=atof(tmp);
timescale=fabs(((4*4.75)/(x[0]-x[1]))*(250/filmspeed));
radiuscale=fabs(od*25.4/(y[2]-y[3]));
for(i=4;i<rawcount;i++)
    {x[i-4]=x[i]*timescale; y[i-4]=y[i]*radiuscale;}
rawcount=rawcount-4;
data_out=fopen(outfile,"w");
fprintf(data_out,"3-%s          Run Number\n\n",&header[5]);
fprintf(data_out,"%f          Mass/Charge Ratio\n",moverc);
fprintf(data_out,"%f          Outside Diameter mm\n",od*25.4);
fprintf(data_out,"%f          Inside Diameter mm\n",id*25.4);
fprintf(data_out,"%f          Explosive Density gm/cc\n",rho);
fprintf(data_out,"%f          Detonation Velocity mm/us\n",DetVel);
fprintf(data_out,"%d          Total Number of Data
Points\n",rawcount);
fprintf(data_out,"\n\nTime(us)          Radius(mm)\n\n");
for(i=0;i<rawcount;i++) fprintf(data_out,"%f          %f\n",x[i],y[i]);
}

```


Analysis Program

This program analysis's the data retrived by the previous program.

```
#include <stdio.h>
#include <math.h>
#include <stdlib.h>
#define PI 3.14159
double x[300],y[300],arry[5][6];
double position[300],vel[300],accel[300],gur[300],vol[300];
char runnum[6],infile[12],outfile[12],outreport[12];
double bisect_time (double,double[5][6],double);
double velocity_of_wall(double,double[5][6]);
double position_of_wall(double,double[5][6]);
double modified_gurney(double,double,double,double,double);
main() {
    FILE *data_in;
    FILE *data_out;
    FILE *report_out;
    int count,i,n,m,nc,mc,npm,j,k;
    char *trash,*tmp;
    double
od,id,moverc,rho,DetVel,err,deter,t,volexp,Ydesired,bitime,v,mgur;
    printf("Key in the input file name "); scanf("%s",infile);
    data_in=fopen(infile,"r");
    printf("\nKey in the output file name "); scanf("%s",outfile);
    printf("\nKey in the report file name "); scanf("%s",outreport);
    report_out=fopen(outreport,"w");
    fscanf(data_in,"%s%s%s",runnum,trash,trash);
    printf("\n Bldg. 1612 Run Number %s",runnum);
    fprintf(report_out,"Bldg. 1612 Run Number %s",runnum);
    fprintf(report_out,"\nFrom data file %s",outfile);
    fscanf(data_in,"%s%s%s",tmp,trash,trash);
    moverc=atof(tmp);
    fscanf(data_in,"%s%s%s%s",tmp,trash,trash,trash);
    od=atof(tmp);
    fscanf(data_in,"%s%s%s%s",tmp,trash,trash,trash);
    id=atof(tmp);
    fscanf(data_in,"%s%s%s%s",tmp,trash,trash,trash);
```

```

rho=atof(tmp);
fscanf(data_in,"%s%s%s%s",tmp,trash,trash,trash);
DetVel=atof(tmp);
fscanf(data_in,"%s%s%s%s%s%s",tmp,trash,trash,trash,trash,trash);
count=atoi(tmp);
fscanf(data_in,"%s%s",trash,trash);
for(i=0;i<count;i++){
    fscanf(data_in,"%s",tmp);
    x[i]=atof(tmp);
    fscanf(data_in,"%s",tmp);
    y[i]=atof(tmp);}
fclose(data_in);
/*initialize array*/
for (n=0;n<5;n++)
    {for(m=0;m<6;m++)
        array[n][m]=0;}
/*Heart of the Array*/
for (n=0;n<5;n++)
    {for (m=0;m<5;m++)
        {for(i=0;i<count;i++)
            if(m+n==0) array[n][m]=array[n][m]+1;
            else {array[n][m]=array[n][m]+pow(x[i],n+m);}}}
/*Vector of the Array*/
for (i=0;i<count;i++)
    {for(n=0;n<5;n++)
        if(n==0) array[n][m]=array[n][5]+y[i];
        else {array[n][5]=array[n][5]+y[i]*pow(x[i],n);}}
printf("\n");
/* simeq */
nc=4;
mc=1;
npm=nc+mc;
err=.0000000001;
deter=1;
for(i=0;i<=nc;i++)
    {deter=deter*array[i][i];
    for(j=i+1;j<=npm;j++) array[i][j]=array[i][j]/array[i][i];
    array[i][i]=1;
    for(j=0;j<=nc;j++)

```

```

        {if(i!=j) {if(array[j][i]!=0)
            {for(k=i+1;k<=npm;k++)
                array[j][k]=array[j][k]-array[j][i]*array[i][k];
            array[j][i]=0;}}}}
fprintf(report_out,"\n\n Array Solution to Least Mean Square Fit \n");
for(i=0;i<=nc;i++)
    {fprintf(report_out,"\n");
    for(j=0;j<=npm;j++)
        fprintf(report_out," %f",array[i][j]);}
/* Gurney Calculations */
data_out=fopen(outfile,"w");
for(i=0;i<count;i++)
    {t=x[i];
    position[i]=position_of_wall (t,array);
    vel[i]=velocity_of_wall (t,array);
    accel[i]=2*array[2][5]+6*array[3][5]*t+12*array[4][5]*t*t;
    gur[i]=vel[i]/(pow(moverc+.5,-.5));
    volf[i]=(pow(y[i]*2+od,2)-pow(od,2)+pow(id,2))/pow(id,2);
    mgur=modified_gurney(vel[i],od,id,moverc,y[i]);
    fprintf(data_out,"%f %f %f %f %f %f %f %f\n"
        ,y[i],position[i],vel[i],accel[i],gur[i],x[i],volf[i],mgur);}
fclose(data_out);
printf("\n");
for (i=2;i<=7;i++)
    {volexp=i*PI*pow(id/2,2)+(PI*(pow(od/2,2)-pow(id/2,2)));
    Ydesired=pow(volexp/PI,.5)-od/2;
    bitime=bisect_time (Ydesired,array,x[count-1]);
    printf("\n");
    fprintf(report_out,"\n");
    printf("\nFor %d Volumes Expansion Time = %f us",i,bitime);
    fprintf(report_out,"\nFor %d Volumes Expansion Time= %f
",i,bitime);
    v=velocity_of_wall(bitime,array);
    printf("\nWith a Wall Velocity of %f",v);
    fprintf(report_out,"\nWith a Wall Velocity of %f mm/us",v);
    printf("\nAnd a Gurney of %f mm/us",v/(pow(moverc+.5,-.5)));
    fprintf(report_out,"\nAnd a Gurney of %f
mm/us",v/(pow(moverc+.5,-.5)));
    mgur=modified_gurney(v,od,id,moverc,Ydesired);

```

```

        printf("\nAnd a Modified Gurney of %f mm/us",mgur);
        fprintf(report_out,"\nAnd a Modified Gurney of %f mm/us",mgur);}
fclose(report_out);
}
/* -----*/
double bisect_time (double Ydesired, double array[5][6],double Tupper)
{double Ygeuss,Tlower,Tmid;
Tlower=0;
while(floor(Ygeuss*100000)!=floor(Ydesired*100000))
    {Tmid=(Tupper+Tlower)/2;
    Ygeuss=array[0][5]+array[1][5]*Tmid+array[2][5]*pow(Tmid,2)+array[3]
][5]*pow(Tmid,3)+array[4][5]*pow(Tmid,4);
    if(Ygeuss > Ydesired) Tupper=Tmid;
    if(Ygeuss < Ydesired) Tlower=Tmid; }
    return Tmid; }
/*-----*/
double position_of_wall (double t, double array[5][6])
{double position;

position=array[0][5]+array[1][5]*t+array[2][5]*t*t+array[3][5]*t*t*t+array[4][5]
*t*t*t*t;
    return position; }
/*-----*/
double velocity_of_wall (double t, double array[5][6])
{double velocity;
    velocity=array[1][5]+2*array[2][5]*t+3*array[3][5]*t*t+4*array[4][5]*t*t*t;
    return velocity; }
/*-----*/
double modified_gurney (double v, double od, double id, double
moverc,double rout)
{double gamma;
double mgur;
double top;
double bottom;
rout=rout+od/2;
gamma=pow(od/2,2)-pow(id/2,2);
top=pow(pow(rout*rout-gamma,.5)/rout,2);
bottom=2*moverc*((rout*rout-
gamma)/gamma)*log(rout/(pow(rout*rout-gamma,.5)))+.5;

```

```
mgur=v/pow((top/bottom),.5);  
return mgur;}  
/*-----*/
```

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